

EFFICIENCY OF USING CFRP LAMINATES WITH AND WITHOUT MECHANICAL END ANCHORAGE IN SHEAR STRENGTHENING OF STEEL I-BEAMS

Hazim AL-Talawy, Ehab F. Sadek, Mohamed A. Khalaf

Abstract-Strengthening of steel structural elements using CFRP laminates has been applied widely in the last few years. The main goal of this research is to evaluate the efficiency of using CFRP laminates in shear strengthening of I-section steel beams. Six steel I-beams were experimentally investigated using four-point load arrangement. First beam was used as a control beam without any shear strengthening. Second and third beams were strengthened in shear by CFRP laminates in two different directions (90° & 45°) without any end-anchorage. Fourth and fifth beams were strengthened in shear exactly like the second and third beams respectively but with mechanical end-anchorage. Last beam was strengthened in shear by the traditional welded steel plates. Stiffness and strength of all the six beams were determined experimentally. Results of the experimental study showed that applying the CFRP laminates improves shear strength and overall stiffness of steel I- beams. Furthermore, using the mechanical end anchorage had significantly improved the load carrying capacity and reduced the deformations and strains especially in the elastic zone.

Index Terms- CFRP laminates, Steel I-beam, Shear strengthening, Mechanical end anchorages, Shear strain, CFRP strain, Shear resistance.

1 INTRODUCTION

Traditional strengthening technique by using steel sections has a good achievement to increase strength and stiffness of steel structural elements. However, this technique has many disadvantages such as it is a labor and cost intensive coupled with the needed onsite welding and drilling operations; it is considered a time consuming technique and consequently can cause a traffic disruption in highway roads and bridges. Moreover, many problems are accompanied with this technique such as the heavy weight of steel plates with a large thickness, carrying and lifting difficulty during construction, a lot of machines and equipment, rust and corrosion problems in iron metal and finally fatigue problems due to stress concentration and weld effect .

Obviously, there is a need to find durable strengthening materials and rapid strengthening techniques. Fiber reinforced polymers (FRP) are latest available alternative materials. FRP became an attractive material in the strengthening field of steel buildings because of its

stunning mechanical and physical properties [1]. Many studies have recently been conducted on the strengthening of steel elements by bonding CFRP laminate to the steel surface .

Flexural strengthening of steel elements using FRP had investigated extensively in many previous studies [2-6]. Another group of studies has focused on strengthening of steel web by CFRP which dramatically increases the web crippling capacity exclusively for those with large web slenderness ratio. Test results proved that there was an increase in the web-buckling capacity especially by bonding CFRP laminates on both sides of the web [7-10].

Shear strength of steel I-beams is controlled mainly by the capacity of the web plate. The collapse of the web plate because of yielding or elastic buckling depends on the slenderness ratio of the web plate. The elastic buckling of the slender web plates is directly related to the level of the major compressive stresses induced within the high shear zones of the beam. Strengthening of steel web by using CFRP materials has the chance to decrease the stress level in the steel web, and subsequently increasing the web shear carrying capacity[2]. Some researchers have demonstrated different techniques for strengthening of steel webs subjected to shear by CFRP .

Patnaik et al. (2008)[11] has published results of an analytical and experimental program focused on shear strengthening of steel built-up I-beams. In this research three steel beams were designed to fail in shear. Two were strengthened by bonding CFRP to the web plates, while the third one was kept un-strengthened control beam for comparison purpose. Test results confirmed the

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effectiveness of shear strengthening application by increasing the shear resistance of the steel beam up to 26% .

Okeil et al. [12-14] has improved the lateral stiffness of buckling-prone steel I-beams by bonding pultruded GFRP sections. Steel I-beams were designed to fail in shear buckling. Thin walled steel web plates were strengthened by GFRP T-shaped in a direction that contributes to the lateral stiffness of the steel web plates more than the in-plane strength as in the popular practice in the most FRP strengthening cases. The strengthened specimen experienced shear buckling under 56% higher load compared with the control un-strengthened specimen. However, the performance of the strengthened specimen was more brittle compared with the control one. This study was continued by Babaizadeh (2012)[15] using Finite Element analysis. Results of the finite element analysis showed that strengthening of steel beams with different flange width can result in the growth of shear capacity up to 66% for square shear zones and up to 36% for the rectangular shear zones. Furthermore, results designated that GFRP stiffeners are more effective than steel stiffener in terms of improving the shear resistance of the strengthened steel beam. However, failures modes of the GFRP stiffened beams are less ductile compared with those of the un-stiffened or the traditionally steel stiffened beams.

Narmashiri et al. (2010)[16] has examined the success of using CFRP as a shear strengthening system. Steel beams were strengthened by applying CFRP on one or both sides of the web using different ratios of CFRP area on the web. Five steel I-section beams were tested. Two beams were strengthened on both sides of the web with the CFRP ratios of 0.72 and 0.48. Two beams were strengthened on one side of web with the CFRP ratios of 0.72 and 0.48. Last beam was kept as un-strengthened control beam to be used for comparison purpose. Results clearly showed that the externally bonded CFRP could increase the shear resistance of the steel strengthened I-beam up to 51%. Furthermore, both CFRP ratios for both sides of web almost had similar level of shear strengthening level.

Elyas Ghafoori, Masoud Motavalli (2015) [23] have studied the elastic behavior of steel beams strengthened by normal, high and ultra-high modulus CFRP strips using bonded and un-bonded systems. Six steel beams strengthened by CFRP strips and one un-strengthened beam (control beam for comparison purposes) were tested statically until failure using four-point load arrangement. The six steel beams were strengthened using normal modulus (NM), high modulus (HM) and ultra-high modulus (UHM) CFRP strips with nominal modulus of elasticity ranging from 165 to 440 GPa. Each type of CFRP strips was attached to the steel beams using bonded reinforcement (BR) and un-bonded reinforcement (UR) systems. The main goal of this research was to study the stress distribution along the beam bottom flange when the BR and the UR systems are used for strengthening. All beams were failed due to lateral

torsional buckling. The obtained test results have shown that strengthening using bonded UHM strips could increase the stiffness of the composite section so that the steel profile has yielded prior to buckling and alarger reinforcement effectiveness was then achieved.

This study was continued both experimentally and numerically by Elyas Ghafoori, Masoud Motavalli (2015) [24] by considering the lateral-torsional buckling of steel beams strengthened by normal modulus CFRP strips. Seven steel beams, (including un-strengthened control beam), were tested statically until failure. Six steel beams were strengthened by bonded and un-bonded CFRP strips. For each type, three steel beams were strengthened by CFRP strips with three different pre-stressing levels (0%, 20% and 40%) and tested till failure. Test results showed that strengthening of steel beams using CFRP strips increases the elastic stiffness of the beams almost the same for both bonded and un-bonded systems compared to the control beam. Pre-stressing of CFRP strips almost has no effect on the stiffness of the strengthened beams but substantially influences the buckling strength. High values of pre-stressing levels do not necessarily lead to an increased buckling strength. In most of the tests, beams strengthened with un-bonded CFRP strips showed slightly higher strength than those strengthened by bonded CFRP strips .

Strengthening of steel beams by using FRP usually suffers de-bonding problem at the end of the FRP laminate. This is normally attributed to the very high stress and strain intensity that occurs at the end of the laminate. I. A. Amer (2016) [25] has conducted an experimental study and detailed analysis of the effectiveness of three different mechanical end-anchoring techniques. Five steel I-beams were tested in flexure using three-point load arrangement. The first beam was un-strengthened and was used as a control beam. The second beam was strengthened by CFRP laminates without any end-anchorage. The other three beams were strengthened by CFRP laminates with three different mechanical end-anchorage techniques using steel plates and bolts (with three different configurations). Test results showed that applying steel plates and bolts to anchor the ends of CFRP laminate is an effective technique. Using mechanical end anchorage significantly improved the load carrying capacity of the strengthened beams and decreased deformation and strains including vertical and lateral deflections. In addition, applying the mechanical end anchorage suppressed the end de-bonding failure and changed the failure mode from sudden to pre-warning failure.

Elyas Ghafoori, Masoud Motavalli (2015) [26] have studied experimentally a system to pre-stress CFRP plates and attach them to existing steel beams for strengthening purpose. The system does not require any glue between the CFRP and steel; therefore, no surface preparation is required, which reduces the time, effort and cost of the

strengthening process. The proposed pre-stressed unbonded reinforcement (PUR) system includes a pair of mechanical clamps that function based on friction. Each clamp can hold and attach three CFRP plates to the steel beam in the same time. Design considerations of clamps (the most important elements in the whole PUR system) were explained. The system has a trapezoidal configuration that offers an easy on-site installation and un-installation procedures without any damage on the steel beam. Three five meters long steel beams were tested until failure, including one non-strengthened control beam and two beams were strengthened with 15% and 31% CFRP pre-stressing levels. A remarkable increase in yielding and ultimate strengths of the strengthened beams was achieved. Compared to the control beam the ultimate load-carrying capacity of the strengthened beams with 15% and 31% CFRP pre-stressing levels increased by more than 23% and 31% respectively.

OBJECTIVES

The main objective of this research is to evaluate the efficiency of using CFRP strips in shear strengthening of built up steel I-beams through an experimental program. A total of six steel I-beams (consisting of one un-strengthened control beam and five strengthened beams by five different techniques) were used in the experimental program. One of the five beams was strengthened by the conventional welded steel plates and the other four beams were strengthened by CFRP strips (using vertical and diagonal (45°) strips - with and without mechanical end anchorage). All the six steel beams were tested in flexure using four point load arrangement until failure. Test results (load-vertical deflection, steel strain and CRFP strain responses) were used to evaluate the efficiency of shear strengthening of steel I-beams using CFRP through the following:

Studying the effect of using CFRP strips (for shear strengthening) on load carrying capacity of steel I-beams and how the CFRP strips can restrict the web shear strains. Load carrying capacity is expressed mainly in terms of the maximum elastic load (load at the end point of the straight line) which is important to designers .

- Studying the effect of changing the CFRP direction (vertical & diagonal 45o) on the load carrying capacity of steel I-beams.
- Studying the effect of using mechanical end anchorage (to fix the ends of CFRP strips) on load carrying capacity and failure mode of the steel I-beams .
- Studying the effect of using CFRP strips (for shear strengthening) on shear resistance ability and web shear strength coefficient of steel I-beams.

- Comparing between strength improvement and overall stiffness improvement for the strengthened beams within the elastic zone.
- Choosing the most effective strengthening technique from the five considered techniques.

2 EXPERIMENTAL PROGRAM

2.1 Test Specimens

Six steel I-beams (steel A36) were used of built up I-section with dimensions shown in Figure (1). This section is a compact section with web height to thickness ratio $h_w/t_w = 25$. The six beams were designed to sustain the flexure stress and to be failed due to shear stresses. Webs of steel beams were supported by group of stiffeners to avoid web crippling or local web buckling as shown in Figure (2). Three steel specimens were cut from the web plates of the beams and were subjected to tension test according to ASTM E8/E8M [17]. Results of the tension test were as follows:

- The average yield strength was 281.5 MPa (SD =1.6 MPa).
- The average ultimate tensile strength was 376 MPa (SD = 3.2 MPa).

Details of the test specimens including their shapes before and after tension failure are given in reference [22].

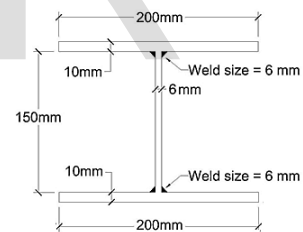


Figure (1): Dimensions of steel I-beam section

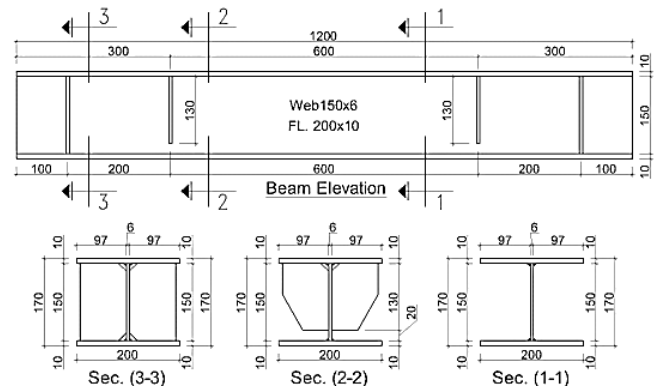


Figure (2): Details and dimensions of the steel I-beams

Tension test was carried out on three CFRP specimens according to ASTM D 3039/D 3039M [18]. Test results were as follows:

- Average value of the tensile strength was 3101 MPa (SD = 79.5 MPa).
- Average value of the strain at peak was 14211 Micro-strain (SD = 250 Micro-strain).
- Average value of the modulus of elasticity was 213367 MPa (SD = 1312 MPa).

Details of the test specimens, their shapes before and after tension failure and the manufacturer data sheet are given in reference [22].

The CFRP laminates were installed on the beam web by using an adhesive material which prepared by mixing two components until and the mix is uniform. Flexure and compression tests were performed on three specimens according to EN-196[19]. Also, Single-lap and double-lap shear tests were performed on three specimens according to ASTM D-5868[20] and ASTM D-3528[21] respectively. Test results were as follows:

- Average flexural strength was 29.45 MPa (SD = 1.56 MPa)
- Average compressive strength was 68.96 MPa (SD = 1.64 MPa)
- Average single-lap shear strength was 13.47 MPa (SD = 0.10 MPa)
- Average double-lap shear strength was 13.11 MPa (SD = 0.14 MPa)

Details of the test specimens, their shapes before and after failure and the manufacturer data sheet are given in reference [22].

Bolts were used to connect the steel anchor plates to the web plate at the CFRP laminate ends. Bolts were of 6 mm diameter and 40 mm length. Tension and shear tests were carried out on the used bolts and the test results were as follows:

- The average yield strength was 980 MPa (SD = 22.4 MPa).
- The average ultimate tensile strength was 1070 MPa (SD = 22.5 MPa).
- The average shear strength was 702 MPa (SD = 14.8 MPa).

Details of the test specimens are given in reference [22].

Six steel I-beams were tested in flexure using four-point load arrangement to study the effect of applying CFRP laminates to increase the shear strength of the steel beams. Two different mechanical end anchorages were suggested to increase the efficiency of using CFRP in enhancing the beams shear strength. Details of the six beams are given in Table (1).

a) The first beam (01-CL) wasn't strengthened and was used as a control beam for comparison purposes. Net grids were plotted on the left and right shear zones as shown in Figure (3).

b) Second and third beams (02-SCLV & 03-SCLD), were strengthened by CFRP laminates vertically (90°) and diagonally (45°) respectively without end anchorage.

c) Fourth and fifth beams (04-SCLVA & 05-SCLDA) were exactly like the second and third beams respectively, but with some action done to fix the ends of the CFRP strips by mechanical end anchorage. Holes were drilled for bolts of the anchorages plates in the web of these two beams. The difference between fourth and fifth beams was the shape of the anchor plates, beam (04-SCLVA) was anchored by two strip plates (at upper and lower ends of CFRP strips - type "A" anchor) while beam (05-SCLDA) was anchored by four sides rectangular anchor plates (at upper, lower, right and left ends of the CFRP strips - type "B" anchor). Details of preparing the steel surface and applying the adhesive material are given in ref.[22]. Here, it is important to notice that drilling holes in beams (04- SCLVA & 05- SCLDA) particularly near to the tension face will reduce the fatigue strength of these beams (since these holes are points of stress concentrations and a source of fatigue cracks initiation). The scope of this research is directed mainly to the static shear strength of steel I-beams strengthened by CFRP strips. Fatigue behavior of these beams needs further study.

d) The last beam (06-SSWP) (beam traditionally strengthened by welded steel plates): Strengthening steel plates (3mm thickness) were cut with the required dimensions and these plates were attached to the web in the left and right shear zone reciprocally by 3 mm weld thickness. Strengthening details and dimensions of all the six beams are shown in Figure (4).

Table (1): Details of steel beams

Beam No.	Code	Beam Description
(01)	CL	Control beam without any shear strengthening
(02)	SCLV	Strengthened by vertical (90°) CFRP strips without end anchorage
(03)	SCLD	Strengthened by (45°) Diagonal CFRP strips without end anchorage
(04)	SCLVA	Strengthened by vertical (90°) CFRP strips with end anchorage
(05)	SCLDA	Strengthened by (45°) Diagonal CFRP strips with end anchorage
(06)	SSPW	Strengthened by traditional welded steel plate

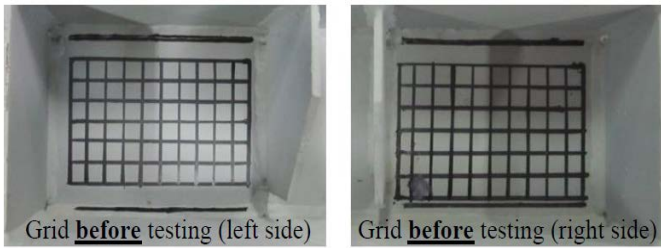


Figure (3): Grids on left and right shear zones before testing for (01-CL)

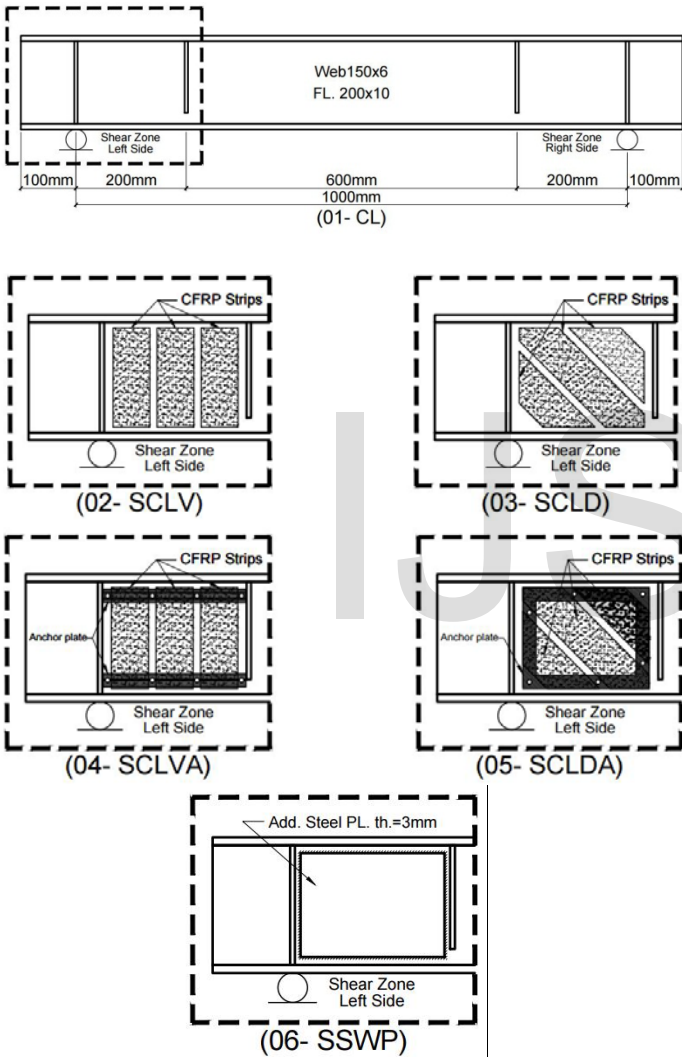


Figure (4): Strengthening details of all beams

2.2 Test set-up and instrumentation

Hydraulic compression testing machine with a capacity of 100 ton was used to test all the six beams. That testing machine was used to apply and measure the load with the required accuracy. The flexure test was performed using a four-point load arrangement. A very rigid steel beam was used to distribute the machine load to two loads applying on the test specimens as shown in Figure (5). In order to

utilize the hydraulic compression testing machine to the four-point loading flexure test, a special test setup was developed and manufactured in Properties and Testing of Materials Laboratory in Faculty of Engineering at Ain-Shams University. The test setup consists of saddle supports, main support beam and four lateral support beams. Test specimens were supported on two saddle supports with a clear span of 1.0m as shown in Figures (5) and (6). Four lateral supports were used to resist lateral torsional buckling that may occur in the beams during the test. It should be noted that the measured lateral deflection of the tested beams was very small (almost negligible).



Figure (5): Test setup

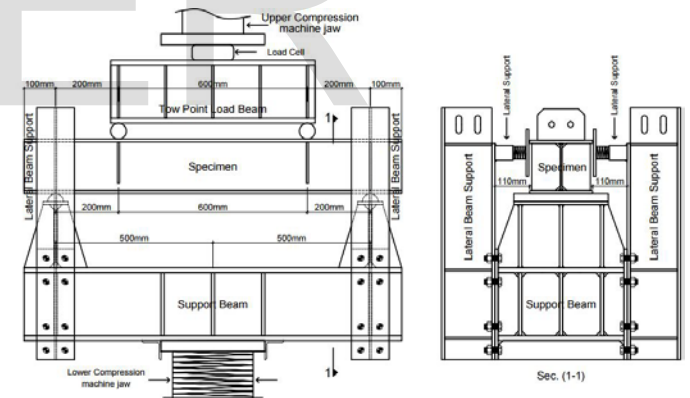
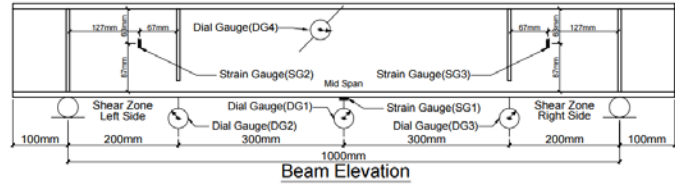


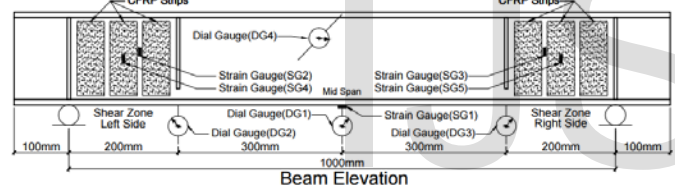
Figure (6): Schematic of the Four-point load arrangement test set-up

Mechanical dial gauges of 30mm gauge length were installed on the specimens in order to measure vertical and horizontal deformations. Electrical strain gauges with 10mm gauge length were installed on the specimens in order to measure shear and flexure strains. Figure (7) show the locations and directions of the used dial gauges and strain gauges for all beams. Dial gauge (DG1) was mounted vertically under the bottom flange of the beams at the mid-span to measure the vertical deflection. Two dial gauges (DG2 and DG3) were mounted vertically under the bottom flange at left and right shear zones of the beam to measure

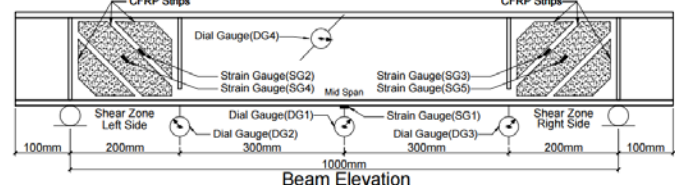
the vertical deflection at these locations. Dial gauge (DG4) was mounted horizontally at the mid-span to measure the lateral deformation of the top flange. The first strain gauge (SG1) was installed to measure the strain in the bottom flange at the mid-span. Two other strain gauges (SG2 and SG3) were installed to measure the strain in the steel web at left and right shear zones. The last two strain gauges (SG4 and SG5) were installed to measure the strain on the CFRP strips at mid-length of CFRP strips in the left and right shear zone. Locations and directions of all dial and strain gauges are shown in Figure (7).



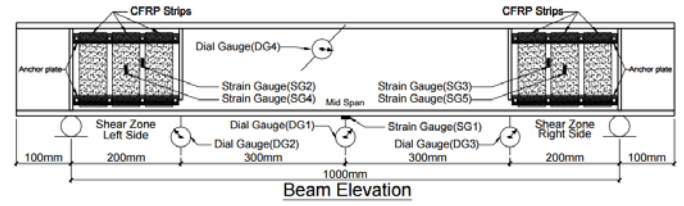
(01-CL - Control beam)



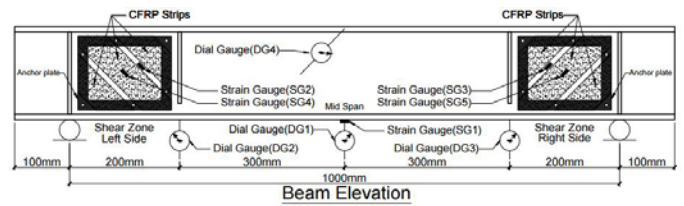
(02-SCLV- Beam strengthened by vertical CFRP without end anchorage)



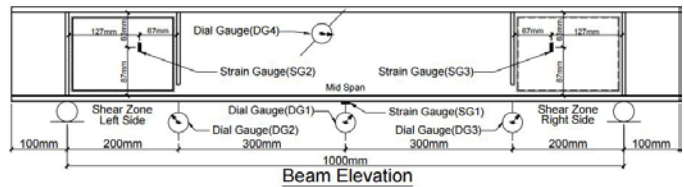
(03-SCLD- Beam strengthened by diagonal CFRP without end anchorage)



(04-SCLVA- Beam strengthened by vertical CFRP with end anchorage)



(05-SCLVA- Beam strengthened by diagonal CFRP with end anchorage)



(06-SSPW - Beam traditionally strengthened by welded steel plate)

Figure (7): Locations and directions of dial gauges and strain gauges

3 TEST RESULTS AND DISCUSSIONS

3.1 Load carrying capacity

The increased percentage of beams load carrying capacity (within the elastic zone) is the most significant parameter that is necessary to evaluate any strengthening technique. Table (2) gives the maximum elastic loads for all the tested

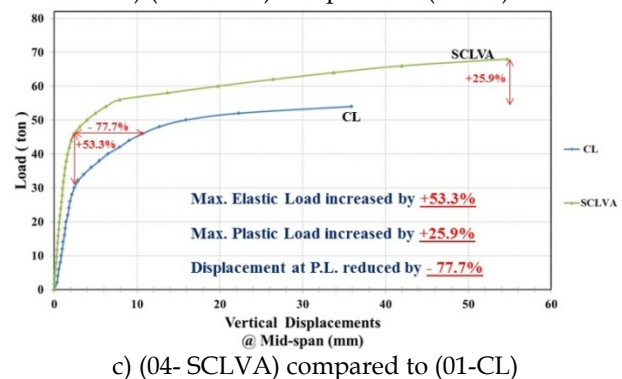
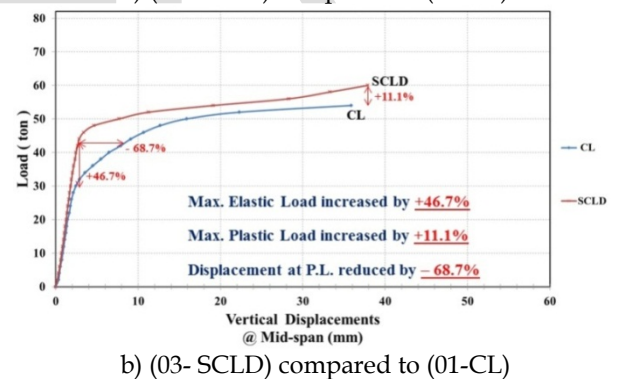
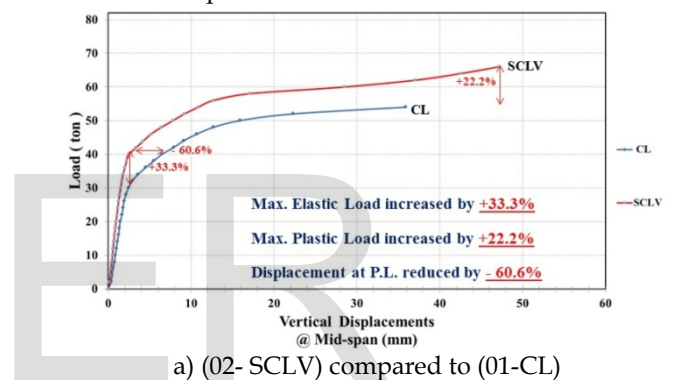
beams. From this table it can be noticed that by applying CFRP on the steel web, the maximum elastic load increased by 33.33% for beam (2) strengthened by vertical CFRP strips and by 46.47% for beam (3) strengthened by diagonal CFRP strips compared with the control beam. When applying mechanical anchorage at the CFRP ends, the maximum elastic load increased by 53.33% for end-anchorage type "A" (two side anchorage for vertical CFRP - beam (4)) compared with the control beam. Similarly the maximum elastic load increased by 73.33% for end-anchorage type "B" (four side anchorage for diagonal CFRP - beam (5)) compared with the control beam. In addition, applying the traditional strengthening method by welding steel plates on the steel web (beam (6)) increased the maximum elastic load by 53.33% compared with the control beam. These test result revealed and emphasized the efficiency of using CFRP in increasing the load carrying capacity of steel I-beams as illustrated in Figure (8). Table (2) shows also that the maximum elastic load increased with applying end-anchorage system type "A" by 15.00% compared with the same beam without end-anchorage. Similarly the maximum elastic load increased by applying end-anchorage system type "B" by about 18.18% compared with the same beam without end-anchorage. This means that using mechanical end-anchorage system has a considerable positive impact on the strengthening efficiency.

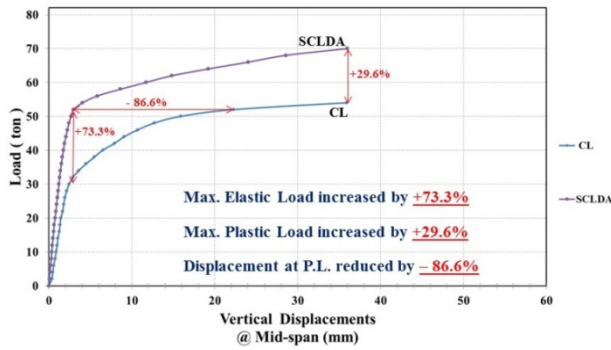
The increase in the maximum elastic loads by applying CFRP laminates to the steel web can be attributed to the composite action. After applying the CFRP to the steel web, the steel web section becomes a composite section with more strong mechanical properties and bigger thickness than the bare steel web section. That is why the maximum elastic load (which is important to designers) increased by the aforementioned percentages. Mechanical end anchorage increases the composite action (by forcing the CFRP strips to resist more loads) and consequently has a considerable positive impact on the strengthening efficiency.

Table (3) gives the ultimate Plastic load for the tested beams. From this table it can be noticed that by applying CFRP on the steel web, the ultimate plastic load of steel I-beams increased by 22.22% for beam (2) strengthened by vertical CFRP and by 11.11% for beam (3) strengthened by diagonal CFRP compared to the control beam. When applying the mechanical end anchorage at the CFRP ends, the ultimate plastic load of the steel I-beams increased by 25.92% for end-anchorage type A and by 29.62% for end-anchorage type B compared to the control beam. In addition, applying the traditional strengthening method by welding steel plates increased the ultimate plastic load by 48.15% compared to the control beam. These result emphasized the efficiency of using CFRP strips in increasing the shear capacity of steel I-beams as illustrated in Figure (8). Table (3) shows also that the ultimate plastic load increased with applying end-anchorage by 3.03% compared with the same beam without end-anchorage

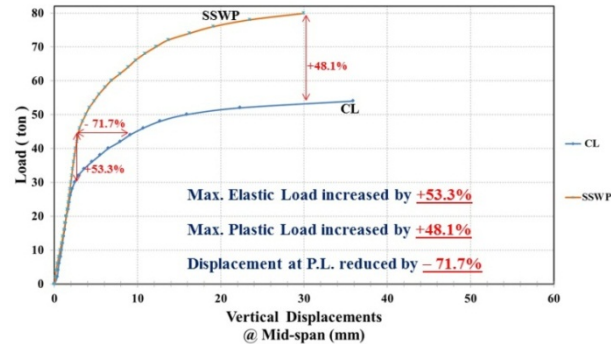
(type A anchorage for vertical CFRP strips), and by about 11.67% compared with same beam without end-anchorage (type B anchorage for diagonal CFRP strips). This means that using end-anchorage system caused a marginal enhancement in the ultimate plastic load compared to non end-anchored beams. It should be noted that within the plastic zone (even after a full separation occurred between CFRP strips and the steel surface) the mechanical end anchorage enforces the CFRP strips to resist loads until a final slippage (between CFRP strips mechanical end anchorage) occurred.

Comparing between the increasing percentages of the maximum elastic and the ultimate plastic loads (given in Tables 2 and 3), it can be easily noticed that using CFRP strips in shear strengthening improves the maximum elastic loads much better than the ultimate plastic loads. This means that the better improvement will be within the elastic zone (before yielding) because of the previously mentioned composite action.





d) (05-SCLDA) compared to (01-CL)



e) (06-SSWP) compared to (01-CL)

Figure (8): Load-Vertical mid span deflection for each beam compared to the control beam

Table (2): Maximum elastic load carrying capacities for all beams

Beam	CFRP end-anchorage system	Max. Elastic Load ton (KN)	Max. Elastic Load increase compared with control beam (%)	Max. Elastic Load increase compared with non-anchorage beam (%)
01-CL	N/A	30 (294.3)	-	-
02-SCLV	N/A	40 (392.4)	33.33	-
03-SCLD	N/A	44 (431.6)	46.47	-
04-SCLVA	Type A	46 (451.3)	53.33	15.00
05-SCLDA	Type B	52 (510.1)	73.33	18.18
06-SSPW	N/A	46 (451.3)	53.33	-

Table (3): Ultimate plastic load carrying capacities for all beams

Beam	CFRP end-anchorage system	Ult. Plastic Load Ton (KN)	Ultimate (Plastic) Load increase compared with control beam (%)	Ultimate (Plastic) Load increase compared with non-anchorage beam (%)
01-CL	N/A	54 (529.7)	-	-
02-SCLV	N/A	66 (647.5)	22.22	-
03-SCLD	N/A	60 (588.6)	11.11	-
04-SCLVA	Type A	68 (667.1)	25.92	3.03
05-SCLDA	Type B	70 (686.7)	29.62	11.67
06-SSPW	N/A	80 (784.8)	48.15	-

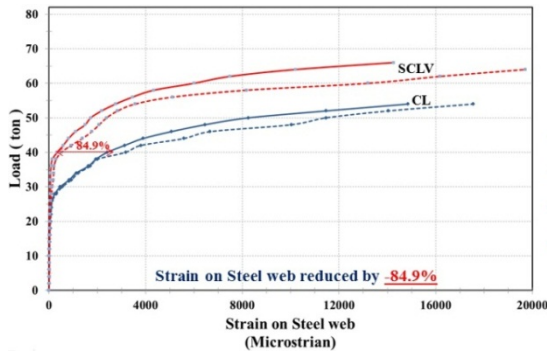
3.2 Steel and CFRP Strains in shear zones

In order to measure strains on the steel web in shear zones, strain gauges were mounted on the steel web in the distance between CFRP strips as described before in section (5). Based on the obtained test results, it can be noticed that using vertical CFRP strips on both sides of the web reduced the steel strain by 84.90% at the proportional limit compared to the control beam as illustrated in Figure (9-a). Using mechanical end-anchorage with vertical CFRP strips reduced the steel strain by 93.70% at the proportional limit compared to the control beam as illustrated in Figure (9-b). For the specimen strengthened by 45° diagonal CFRP strips, it was found that steel strain reduced by 76.40% compared to the control beam as illustrated in Figure (10-a). Moreover, when applying the end-anchorage to the diagonal CFRP strips, the steel strain reduced by 78.70% compared to the control beam as illustrated in Figure (10-b). In addition, it was observed that the reduction in shear strain obtained by the traditional strengthening system is 94.5% which is almost the same reduction by using vertical strips with end-anchorage as illustrated in Figure (9-c).

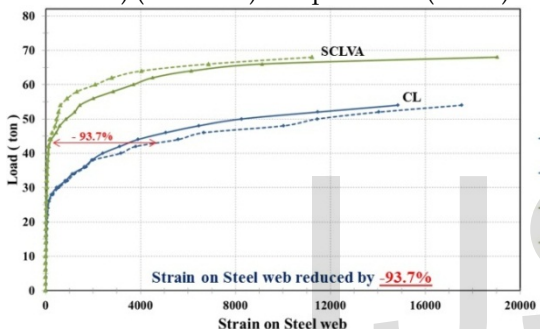
Using CFRP strips increases the web thickness and makes the steel web more restricted (due to the composite action) and consequently reduces both stresses and strains acting

on the steel web remarkably leading to an increase in the beam load carrying capacity. Using mechanical end-anchorage to fix the CFRP ends will increase the restriction level and consequently increase the beam load carrying capacity more than the same beams without mechanical end-anchorage as illustrated in Figures (9-d) and (10-c).

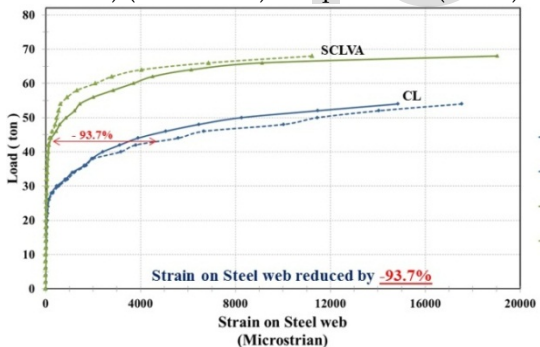
Figure (9): Load-Steel strain curves at left and right shear zones for beams (1,2,4,6)



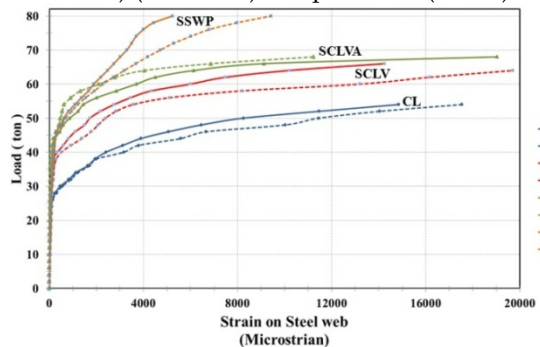
a) (02- SCLV) compare with (01-CL)



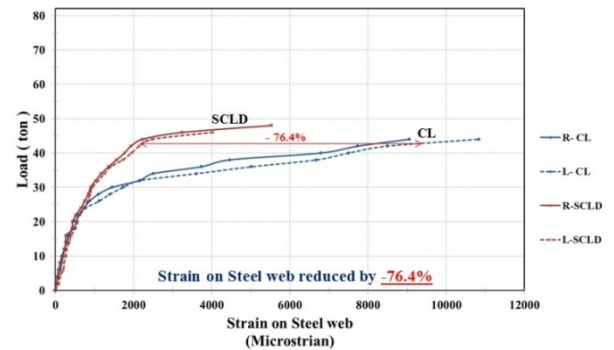
b) (04- SCLVA) compare with (01-CL)



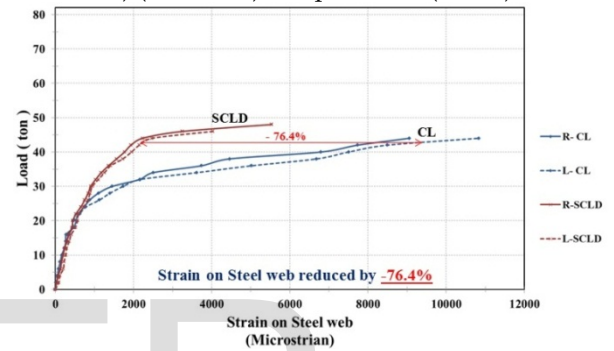
c) (06- SSWP) compare with (01-CL)



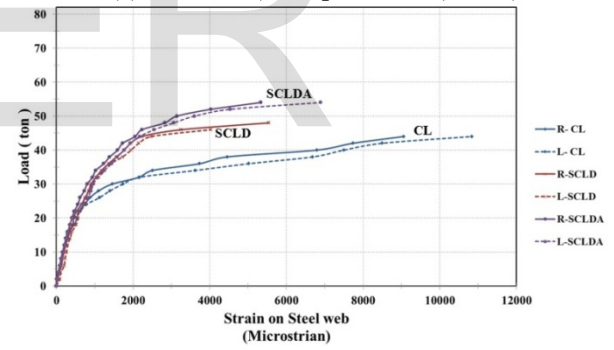
d) (01-CL), (02-SCLV), (04-SCLVA) and (06-SSWP)



a) (03- SCLD) compare with (01-CL)



b) (05- SCLDA) compare with (01-CL)



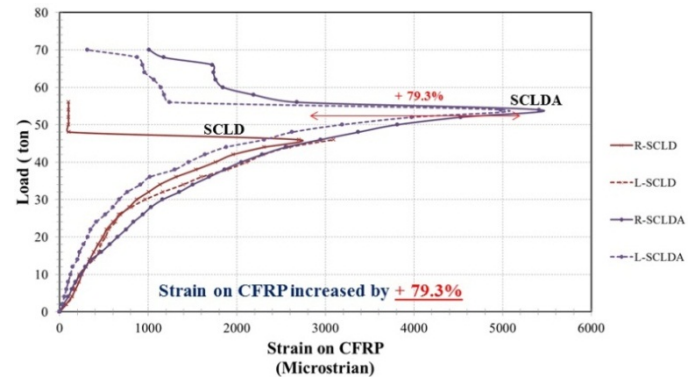
c) (01-CL), (03-SCLD) and (05-SCLDA)

Figure (10): Load-Steel strain curves at left and right shear zones for beams (1,3,5)

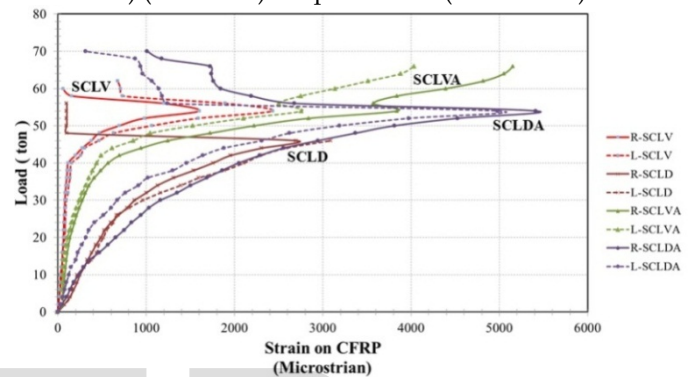
Tensile strain was generated in CFRP strips because of the restriction of the steel web. Tensile strain generated in the CFRP strips is considered important sign to the effectiveness of using CFRP strips and mechanical end anchorage systems. Applying CFRP strips on the steel web reduced the steel web strains remarkably as mentioned before and delayed the yielding point by a significant value due to the aforementioned restriction. CFRP strains test results showed that applying the end anchorage on the CFRP ends increased the CFRP strains. For vertical CFRP strips, strain in beam (04-SCLVA) was 63.70% more than that in beam (02-SCLV) as illustrated in Figure (11-a). For

diagonal CFRP strips, strain in beam (05-SCLDA) was 79.30% more than that in beam (03-SCLD) as illustrated in Figure (11-b). Figure (11-c) shows the load-strain test results for beams 2, 3, 4 and 5. From this figure, it can be noticed that the strain in the diagonal strips (beams 3 and 5) is generally higher than that in the vertical strips (beams 2 and 4). Also from Figure (11-c) it can be noticed that CFRP strips in beam (5) (diagonally strengthened with end anchorage) is the most stressed CFRP strips compared with CFRP strips in all other beams.

Based on the obtained test results, and by comparing between the measured strains in vertical and diagonal CFRP strips (comparing between beams 2 and 3 without end anchorage & comparing between beams 4 and 5 with end anchorage), it can be noticed that CFRP strips in the diagonal direction (45°) are generally more effective in shear strengthening than those in the vertical direction. The effectiveness of using diagonal CFRP strips appeared in a higher stresses and strains, higher elastic and plastic load-carrying capacities and higher restriction level than the case of using vertical strips. This can be attributed to that the main tension force acting on the steel web (in shear zone) is the diagonal tension force in 45° direction resulting from shear forces acting on the web. Diagonal (45°) strips resist the full value of the diagonal tension force because the strips are in the same direction with this force while the vertical strips resist only the vertical component of this force. That is why the diagonal strips are more stressed than the vertical strips as mentioned before. This is exactly like the difference between vertical and diagonal stirrups in RC beams subjected to shear forces. Diagonal stirrups are more effective in resisting shear forces than vertical stirrups because of the same reason. Anchored diagonal strips are more effective than the non-anchored diagonal strips because the mechanical end anchorage enforces the strips to continue resisting loads even after a full separation (between CFRP strips and steel surface) occurred. In this case the CFRP strips will continue resisting loads until slippage occurred (slippage between CFRP strips and mechanical end anchorage).



b) (03- SCLD) compared with (05- SCLDA)



c) (02- SCLV), (03- SCLD), (04- SCLVA) and (05- SCLDA)
Figure (11): Tensile strain on CFRP strips

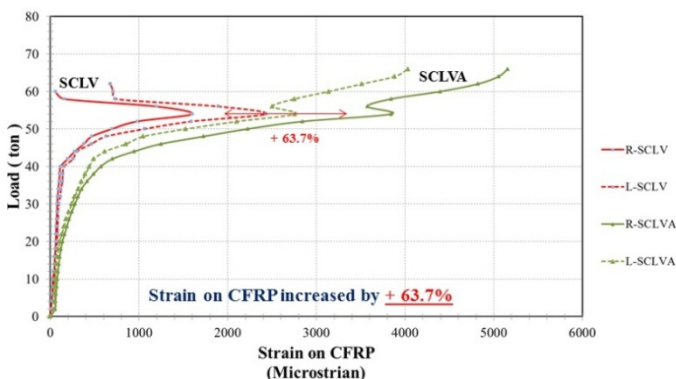
3.3 Failure modes

Modes of failure were different from one beam to another. For the control beam (01-CL) and as illustrated through the grid in figure (12), the failure mode was steel yielding followed by web shear buckling which was expected since the beam section was designed as a compact section.

For the strengthened beams by vertical and diagonal CFRP strips without end anchorage (beams 02- SCLV and 03-SCLD respectively), the failure mode was due to steel yielding followed by web shear buckling accompanied by gradual separation between CFRP strips and steel surface. Separation started almost the proportional limit and continued gradually (strip by strip) until a complete failure occurred as shown in Figures (13) and (14).

Modes of failure for CFRP strengthened beams before and after the mechanical end anchoring were not the same. For beam (04- SCLVA) strengthened by vertical CFRP strips with mechanical end anchorage, the failure occurred as follows:

- Separation between CFRP strips and steel surface started in the middle part of the strips. Initiation of this separation happened almost at the load at the proportional limit (end point of the straight line).
- Yielding occurred in the steel web and consequently large deformation occurred. The separation between CFRP and steel surface continued gradually (strip by



a) (02- SCLV) compared with (04- SCLVA)

strip) from middle towards ends of the CFRP strips. During the spread of this separation, the tensile stresses on the CFRP strips increased gradually due to the restriction done by the mechanical end anchorage. Mechanical end anchorage enforces the strips to resist more loads even after the full separation occurred.

- After yielding and during the separation, web shear buckling was occurred until the point of complete failure. Complete failure occurred in this beam without final slippage between CFRP strips and the mechanical end anchorage because the vertical strips were subjected to the vertical component only of the acting diagonal tension force as mentioned before. Failure of beam (04- SCLVA) is shown in Figure (15).

For beam (05- SCLDA) strengthened by diagonal CFRP strips with mechanical end anchorage: Failure occurred exactly like that occurred in beam (04- SCLVA). The only difference is that the CFRP strips were subjected to slippage from the end anchorage after the full separation. The reason behind that is the diagonal strips are subjected to the full value of the diagonal tension force while the vertical strips are subjected to the vertical component only (diagonal strips were more stressed than the vertical strips). That is why the slippage happened in the diagonal strips and did not happen in the vertical strips. Failure of beam (05-SCLDA) is shown in figure (16). It can be noticed that the maximum strain in diagonal CFRP strips is higher than that in the vertical strip as discussed earlier in section (6.2.2.b). That is why beam (04- SCLVA) showed relatively more ductile behavior than beam (05- SCLDA).

Separation of CFRP strips (strip by strip) and final slippage in mechanically end anchored beams can be considered an apparent ductile indication of failure. So that, it can be said that using mechanical end-anchorage for CFRP strips increased the utilization efficiency and changes the failure mode to a relatively pre-warning failure.

For the last beam strengthened by the traditional welded steel plates (06-SSWP): the failure mode was sudden due to a sudden crack in the weld (accompanied with a high sound) and consequently a sudden drop in the applied load. The sudden drop in the applied load is attributed to that the load (before the weld failure) was resisted by 9 mm web thickness and suddenly after the weld failure it was resisted by the original 6 mm web thickness. After the sudden collapse in the welding area, web yielding was occurred followed by web shear buckling as shown in Figure (17). It is very important to note that the sudden drop in the applied load was not recorded or plotted and the last recorded and plotted load value was that just before the sudden failure. That is why the load-vertical deflection curve for this beam was not complete and the curve was stopped just before the point of the sudden failure. This curve is illustrated clearly in figures (8-e, 18 and 19).

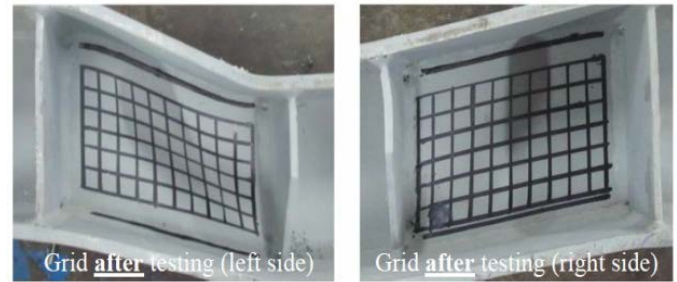


Figure (12): Grids in the left and right shear zone after testing control beam(01-CL)



Figure (13): CFRP separation in left shear zone for beam (02-SCLV)

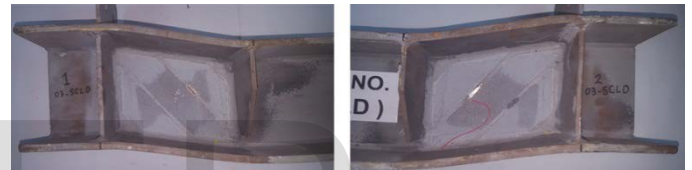


Figure (14): CFRP Separation in both shear zones for beam (03-SCLD)



Figure (15): CFRP Separation in both shear zones without slippage for beam (04-SCLVA)



Figure (16): CFRP Separation and slippage in both shear zones for beam (05-SCLDA)



Figure (17): Shear buckling of the steel web with a failure beside the welding area in left shear zone (beam 06-SSWP)

3.4 Vertical deflection

The value of beam vertical deflection might be considered important criteria by which the efficiency of any strengthening system could be well estimated and evaluated. The reduction in vertical deflection after strengthening is a major sign of the success of a certain strengthening technique. A comparison between load-deflection curves for the control beam and the five strengthened beams is shown in Figures (18) and (19). Figure (18) shows a comparison between load-vertical deflection curves for beams strengthened by vertical CFRP strips with and without end anchorage (02-SCLV and 04-SCLVA respectively) compared with the control and the traditionally strengthened beams (01-CL and 06-SSWP respectively). Figure (19) shows a comparison between load-vertical deflection curves for beams strengthened by diagonal CFRP strips with and without end anchorage (03-SCLD and 05-SCLDA respectively) compared with the control and the traditionally strengthened beams.

Figures (18) and (19) show that the slope of the straight line for strengthened beams is higher than that for the control beam. Overall stiffness of beams is expressed in terms of the slope of the straight line within the elastic zone. Table (4) gives the overall stiffness for all the strengthened beams compared with the control beam. From this table it can be noticed that the overall stiffness of non end-anchored vertical and diagonal CFRP strengthened beams increased by 43.1% and 23.9% compared to the control beam respectively. Similarly the overall stiffness of the end-anchored vertical and diagonal CFRP strengthened beams increased by 89.6% and 65.4% compared to control beam respectively. Overall stiffness of the traditionally strengthened beam using welded steel plates was increased by 16.8% compared to the control beam.

It is well known that the beam total vertical deflection (under vertical loads) is a summation of flexural deflection and shear deflection.

For beams where the major acting stresses are the flexural stresses, the percentage of flexural deflection from total deflection is higher than the percentage of shear deflection. In this case the flexural rigidity of beams is expressed mainly in terms of "EI" ("E" is the beam material modulus of elasticity and "I" is the inertia of beam cross section).

For beams where the major acting stresses are the shear stresses (case of short span beams as in this research) the percentage of shear deflection from total deflection is higher than the previous case. In this case shear rigidity of beams is expressed mainly in terms of "GAw" ("G" is the shear modulus of the beam material and "Aw" is the web cross sectional area).

Attachment CFRP strips to the steel web will increase both values "G" and "Aw". The increase in the value of "G" is attributed to the composite action (since "G" will be the shear modulus of the composite section which is higher

than that of the bare steel section). Similarly "Aw" is the web cross sectional area of the composite section which is also higher than that of the bare steel web section.

The beam overall stiffness is expressed in terms of the slope of the straight line. The overall stiffness of CFRP strengthened beams within the elastic zone was higher than that of the control beam due to the composite action as discussed in the previous paragraph. Table (4) shows that the increase in the overall beam stiffness for the case of vertical strips is higher than that for the case of diagonal strips. This is a completely different situation than what happened in the strength. Vertical strips increase both strength and stiffness of the web section in the vertical direction. Increased web stiffness in the vertical direction means that the web will be more resistant to vertical deflection under vertical loads. Diagonal strips increase the web strength and stiffness in the diagonal direction (so that the web will be more resistant to the diagonal tension force as mentioned earlier) but only the vertical component of the CFRP stiffness will contribute in resisting the vertical deflection. That is why the vertical strips are more effective in resisting the vertical deflection (i.e. more effective in stiffness) while the diagonal strips are more effective in resisting the diagonal tension force resulting from shear stresses (i.e. more effective in shear strengthening)

It is worthy here to compare between strength and overall stiffness for all the six beams within the elastic zone. As shown in Table (5) using CFRP strips improved beam stiffness as well as beam strength within the elastic zone. Strength was increased by a percentage ranging from (33%) to (73%) compared with the control beam (strength was expressed in terms of the maximum elastic load as discussed earlier in sections 6.1.a, b, d). Similarly the overall stiffness increased by a percentage ranging from (23%) to (89%) compared to the control beam. Traditionally strengthened beam by welded steel plate showed an increase in the strength by 53.3% and in the overall stiffness by 16.8%.

Table (4): Overall stiffness of all beams

Beam No.	01-CL	02-SCLV	03-SCLD	04-SCLVA	05-SCLDA	06-SSWP
Overall stiffness	12.997	18.594	16.100	24.644	21.493	15.184
Ton/mm (KN/mm)	(127.5)	(182.4)	(157.9)	(241.8)	(210.8)	(149.0)
% From control	100	143.1	123.9	189.6	165.4	116.8

Table (5): Comparison between strength increase and overall stiffness increase for all beams within the elastic zone (compared with control beam)

Beam No.	01-CL	02-SCLV	03-SCLD	04-SCLVA	05-SCLDA	06-SSWP
Strength (% From control)	100	133.3	146.5	153.3	173.3	153.3
Stiffness (% From control)	100	143.1	123.9	189.6	165.4	116.8

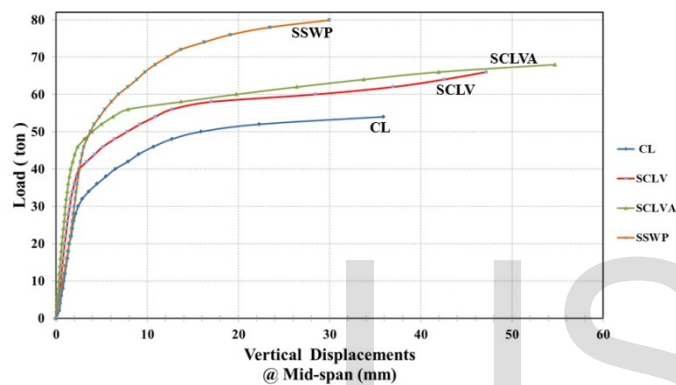


Figure (18): Load-mid span deflection curves for the specimens (01-CL), (02-SCLV), (04-SCLVA) and (06-SSWP)

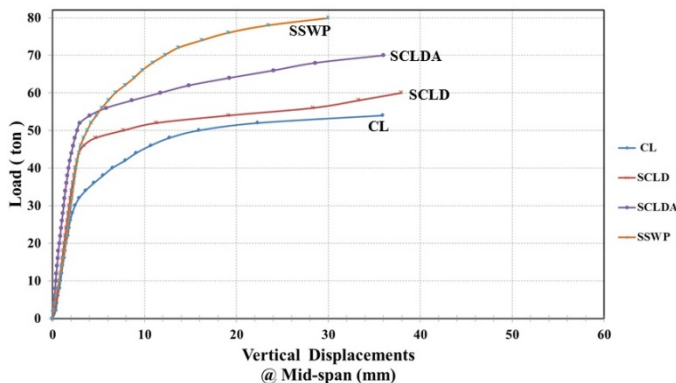


Figure (19): Load- mid span deflection curves for the specimens (01-CL), (03-SCLD), (05-SCLDA) and (06-SSWP)

3.5 Web shear strength

The following equation (equation (1)) is used to calculate the nominal shear strength “ V_n ” for stiffened or un-stiffened compact webs according to the limit states of shear yielding and shear buckling (according to AISC - Chapter G) (Ref.(27)). According to the dimensions of the tested steel beams, the beam section is a compact section

(failure is designed to be occurred by yielding followed by web shear buckling - $h_w/t_w = 25$, $C_{v1}=1.0$).

$$V_n = 0.6 F_Y A_w C_{v1} \dots\dots\dots \text{Equation (1)}$$

For $h/t_w \leq 1.10 * \sqrt{\frac{k_v * E}{F_y}}$; $C_{v1} = 1.0$ &for stiffened webs, $k_v = 5 + \frac{5}{(a/h)^2}$

Where;

a = clear distance between transverse stiffeners.

h = the clear distance between flanges, for built-up welded sections.

E = steel modulus of elasticity.

F_y = specified minimum steel yield stress.

A_w = area of web (the overall web depth times the web thickness).

Shear resistance ability of steel I-beams is defined as the maximum recorded elastic load resisted by the beam “P” and equals to twice the nominal shear strength “ V_n ” (i.e. $P=2V_n$). Shear resistance ability of steel I-beams depends on the web dimensions and its material properties. Shear resistance ability of steel I-beams makes use of only 60% from the steel yielding stress as stated by equation (1). Strengthening the steel web by CFRP strips enhance the behavior of the web and its shear resistance ability (due to the composite action) leading to exploiting of more than 60% from the steel yielding stress. This ratio (i.e. 60% which referred as web shear strength coefficient) is valid only for steel webs without CFRP strips (i.e. for control beam (01-CL) and traditionally strengthened beam with steel plates (06-SSPW)).

Test results showed that by applying the vertical CFRP strips to the steel web on both sides, the shear resistance ability of steel I-beams increased by 28.30% (beam without end anchorage) and by 41.70% (beam with end anchorage) compared to control beam as given in Table (6). For beams strengthened by 45° diagonal CFRP strips, the shear resistance ability increased by 48.30% (without end anchorage) and by 65.00% (with end anchorage) compared to control beam as given in Table (6).

Equation (1) is used to calculate the nominal shear strength for steel webs due to yielding of web (for compact section as in our case).

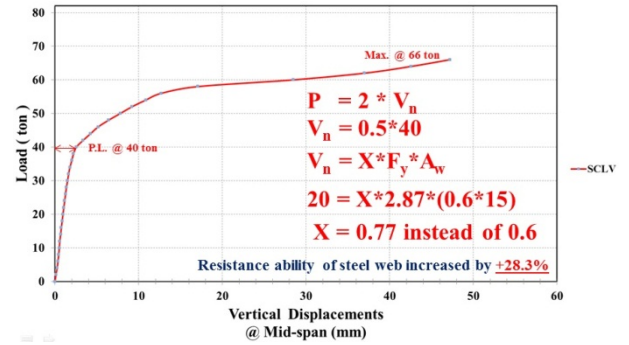
This equation is used for beams (1&6) (control beam and traditionally strengthened beam) – The web shear strength coefficient in this equation is 0.6 (i.e. 60% from web yielding stress).

For beams 2, 3, 4, 5 strengthened with CFRP strips: Because of the composite action, the experimentally measured values of the maximum elastic loads (at the proportional limit) were used as equivalent yield loads for these beams and consequently the new values of the web shear strength coefficient (which is only 60% for beams 1 and 6) can be easily calculated. The values of web shear strength coefficient are (77%, 85%, 89%, 99%) for beams (2, 3, 4, 5) respectively. These values are higher than 60% as given in Table (6). Figure (20) shows the load at the proportional limit for the all six beams and the detailed calculations of the web shear strength coefficient.

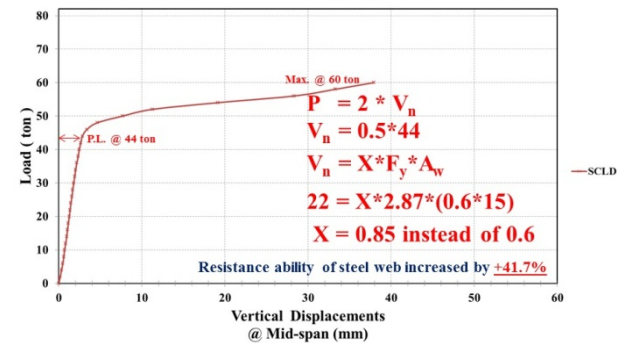
Based on the results given in Table (6) and shown in Figure (20), the increase in the maximum elastic loads (which is important to designers) is the major improvement in this research. The level of improvement varies with the direction of CFRP and with using the mechanical end anchorage (the experimental parameters considered in the research).

From Table (6), it can be seen that the diagonal CFRP strips are more effective in shear strengthening of steel I-beams than the vertical strips. For vertical and diagonal CFRP strips without end anchorage, the calculated values of web shear strength coefficient were 77% and 85% respectively. For vertical and diagonal CFRP strips with end anchorage, the calculated values of web shear strength coefficient were 89% and 99% respectively.

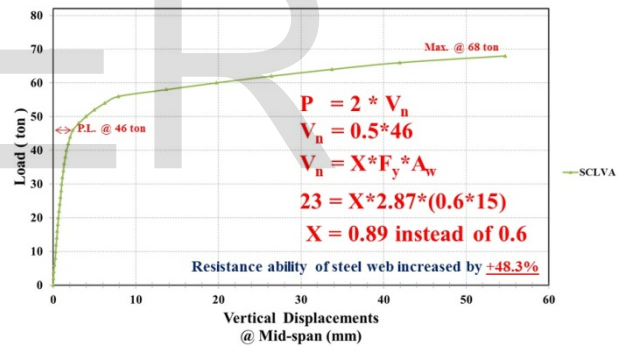
Strengthening technique using diagonal CFRP strips with mechanical end anchorage is considered the most effective technique since it has the highest value of the web shear strength coefficient (equals to 0.99). This conclusion supports strongly the earlier discussion in section (6.2.2.b) about the effectiveness of the diagonally anchored CFRP strips.



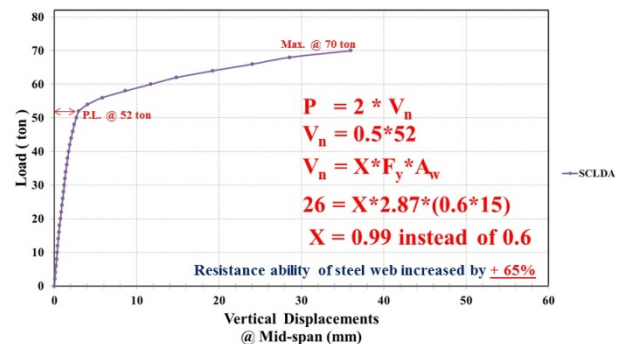
b) (02- SCLV)



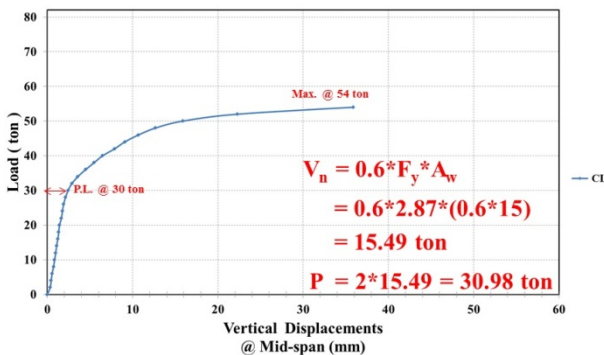
c) (03- SCLD)



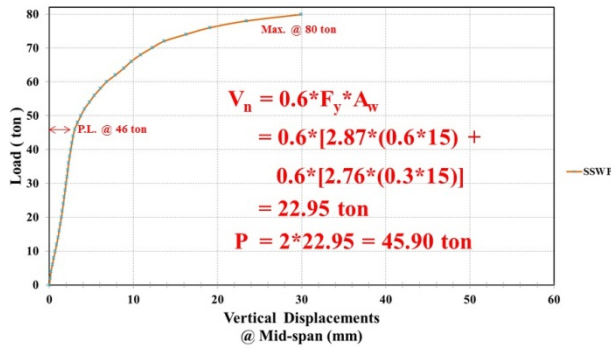
d) (04- SCLVA)



e) (05- SCLDA)



a) (01-CL)



f) (06-SSWP)

Figure (20): Shear resistance ability and web shear strength coefficient for all beams

Table (6): Shear resistance ability and web shear strength coefficient for all beams

Specimen	Shear resistance ability "P" [ton (KN)]	Web shear strength coefficient (%)	Increase in web shear strength coefficient (%) compared to control and conventionally strengthened beams (beams 1 & 6)
01-CL	31 (304.11)	60 %	-
02-SCLV	40	77 %	+28.30
03-SCLD	44	85 %	+41.70
04-SCLVA	46	89 %	+48.30
05-SCLDA	52	99 %	+65.00
06-SSPW	46	60 %	-

4 CONCLUSIONS

Based on the obtained test results of the experimental program, comparison between the five different shear strengthening techniques with the control case and the discussion of test results, the following points can be concluded:

1- Using CFRP strips (with and without mechanical end-anchorage) improves shear strength and stiffness of steel I-beams. CFRP strips increase load carrying capacity of the steel I-beams (by increasing maximum elastic and ultimate plastic loads), decrease the steel web shear strains (by doing more restriction on the steel web) and increase the overall beam stiffness. The better improvement is in the value of the maximum elastic load (at the end of the straight line) which is important to designers.

Compared with control beam, non end-anchored CFRP vertical and diagonal strips:

- Will increase the maximum elastic load by 33.3% and 46.7%, respectively.
- Will increase the ultimate plastic load by 22.2% and 11.1%, respectively.
- Will increase the overall beam stiffness by 43.1% and 23.9%, respectively.
- Will decrease the web shear strain by 84.9% and 76.4% respectively.

Compared with control beam, end-anchored CFRP vertical and diagonal strips:

- Will increase the maximum elastic load by 53.3% and 73.3% respectively.
- Will increase the ultimate plastic load by 25.9% and 29.6%, respectively.
- Will increase the overall beam stiffness by 89.6% and 65.4%, respectively.
- Will decrease the web shear strain by 93.7% and 78.7% respectively.

2- Using mechanical end anchorage increases the load carrying capacity of steel I-beams. Mechanical end-anchorage for vertical and diagonal CFRP strips increases the maximum elastic load by 15.00% and 18.18% respectively and increases the ultimate plastic load by 3.03% and 11.67% respectively compared with the same cases without end anchorage.

3- Using mechanically end-anchored CFRP strips increases the utilization efficiency and changes the failure mode to a relatively pre-warning failure. Failure modes of CFRP strengthened beams with mechanical end-anchorage had an apparent ductile indication before failure in terms of steel yielding and gradual separation of CFRP strips followed web shear buckling and finally full slippage from the end anchorage.

4- Using CFRP strips increases the shear resistance ability of steel web remarkably. The web shear strength coefficient increased from 60% (for steel webs without CFRP strips) to 77% and 85% for steel webs with vertical and diagonal non end-anchored CFRP strips respectively and to 89% and 99% for steel webs with vertical and diagonal end-anchored CFRP strips respectively.

5- Diagonal CFRP strips (45°) are more effective in shear strengthening than vertical strips (either with or without mechanical end anchorage). On the other hand the vertical strips are more effective to increase the overall stiffness than the diagonal strips.

6- Shear strengthening using diagonal CFRP strips with mechanical end-anchorage is considered the most effective shear strengthening technique. On the other hand using vertical CFRP strips with mechanical end-

anchorage is considered the most effective technique to increase the beam overall stiffness.

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